Continuing Investigations of the Relationship Between Fin Whales, Zooplankton Concentrations and Hydrothermal Venting on the Juan De Fuca Ridge

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LONG-TERM GOALS

We are investigating the potential correlation between fin whale tracks, enhanced zooplankton concentrations and hydrothermal vents above the Juan de Fuca Ridge. Our goal is to understand the influences of globally distributed hydrothermal plumes on the trophic ecology of the deep ocean.

OBJECTIVES

We are continuing a study of seismic and bio-acoustical data sets from the Juan de Fuca Ridge with the following three objectives:

1. Complete the detailed analysis of a data set of several hundred thousand fin whale calls recorded on the Endeavour segment over a 3-year period from 2003-2006.
2. Estimate the density of calling fin whales above ocean bottom seismometers deployed at mid-plate locations on the Explorer and Juan de Fuca plates and near the continental margin in order to test whether the density of vocalizing fin whales is unusually high around the Endeavour vent fields.
3. Complete the calibration of Acoustic Doppler Current Profiler (ADCP) backscatter intensities in terms of biomass and apply the results to historical and NEPTUNE Canada ADCP data to understand the relationship between the seasonal migration patterns of zooplankton and their enhanced concentrations within the water column above the hydrothermal vents.

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APPROACH

The W. M. Keck Foundation supported an experiment on the Endeavour segment of the Juan de Fuca Ridge that included a network of eight ocean bottom seismometers (OBSs) that operated from 2003-6. The experiment also included one-year deployments of OBSs on the Explorer plate and the continental slope offshore Nootka Sound (Fig. 1). More recently, NEPTUNE Canada has commenced seismic observations at 4 nodes on their cabled observatory including the Endeavour segment (Fig. 1). The OBS records include a very extensive data set of fin and, to a lesser extent, blue whale vocalizations. Previous work (e.g., McDonald *et al.*, 1995; Rebull *et al.*, 2006) has shown that seafloor seismic networks can be used to track fin whales but the data sets have been limited to a few tracks. Our approach to analyzing the Endeavour network data is to develop an automatic tracking algorithm (Wilcock, 2012) that picks times of direct and multipath arrivals based on finding peaks in the instantaneous amplitude of the seismic records and uses a grid search approach to find the location that matches the observed arrival times best. The whale tracks can then be combined with calling patterns determined using a matched filter or spectrogram cross-correlation detector to investigate the behavior of vocalizing whales and their distribution relative to the vent fields. To determine call densities from call counts on single isolated OBSs requires a method to estimate the range of calls. To accomplish this we estimate the fin whale source levels using calls located with the Endeavour network and develop a technique to estimate the range of fin whales using the spacing and amplitude of multipath arrivals.

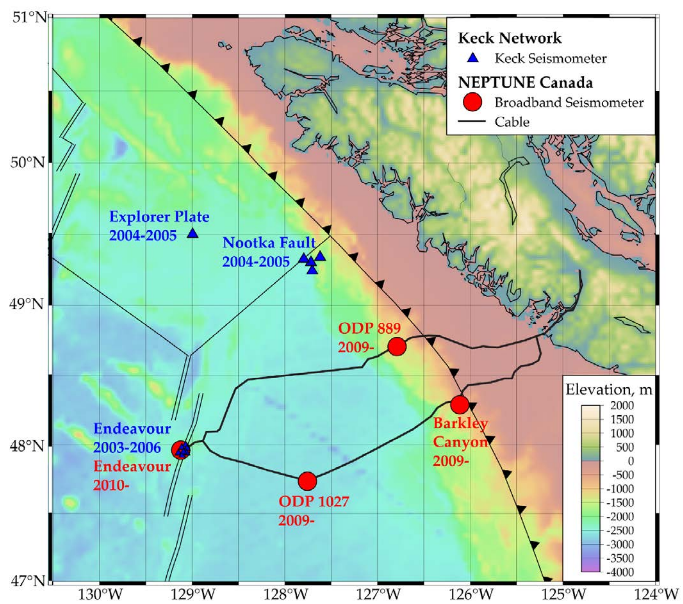

Fig. 1. Map of the NE Pacific Ocean off Vancouver Island showing the locations of seismometers deployed in the Keck experiment and broadband seismometers on the NEPTUNE Canada cabled observatory.

In the early to mid-1990s, the Institute of Ocean Sciences in Sidney, BC conducted summer cruises to the Endeavour to collect a series of plankton net tows in conjunction with measurements including acoustic backscatter intensity. The prior analysis of net samples collected in 1991-4 shows enhanced zooplankton concentrations at all depths above the hydrothermal vent fields (Burd and Thomson, 1994, 1995). At depth, the zooplankton are concentrated in a layer of increased acoustic backscatter near the

top of the hydrothermal plume (Thomson *et al.*, 1991; Burd *et al.*, 1992), leading to the inference that the zooplankton are grazing on the plumes. Community analysis shows that the deep faunal assemblages above the vents are infiltrated by shallow species, which presumably migrate vertically between the upper ocean and the hydrothermal plume (Burd and Thomson, 1994, 1995). Our approach is to analyze additional net samples collected in the area from 1995-6 to identify major zooplankton and fish species and determine length, gender, stage of development, and dry/wet biomass. The expanded zooplankton data set can be used to refine our understanding of variations in zooplankton concentrations with distance from the hydrothermal vent fields. The data on zooplankton distribution and biomass in the water column overlying Endeavour Ridge are well suited to acoustic calibration of net samples because the ADCP was mounted just below the multiple-net apparatus and the attitude sensors and current measuring capabilities of the ADCP allowed us to determine the flow volume with only 2 to 3% error (Burd and Thomson, 1993). A close regressional relationship between the biomass and acoustic backscatter (for the specified scattering cross-sectional model) means that profile acoustic data can be used to map three-dimensional distributions of biomass in the vicinity of the ridge without the need for expensive and labor intensive net sampling tows. The relationship can be used to interpret upward looking ADCP data collected in the Axial Valley with autonomous instruments deployed from 2003-6 and with the NEPTUNE Canada cabled observatory starting in 2010.

WORK COMPLETED

1. *Whale Tracking.* In previous reporting periods, we described an arrival time picking and locating algorithm for fin whales, investigated the incorporation of additional constraints from amplitude and particle motions, and demonstrated the use of a cross-correlation and double difference method (Waldhauser and Ellsworth, 2000) to refine tracks. We described the application of this to the Endeavour data to obtain >150 fin whale tracks. In this reporting period, we published the results in two papers in the *JASA* (Wilcock, 2012; Soule and Wilcock, 2013).

2. *Whale Call Densities.* In previous reporting periods, we evaluated two automated methods to detect fin calls using matched filters and spectral cross-correlation (Weirathmueller *et al.*, 2011) and obtained call counts normalized to a uniform background noise level for sites on the Endeavour ridge, Nootka fault and middle of the Explorer and Juan de Fuca plates (Fig. 1). In this reporting period we published a paper in the *JASA* that presented estimates of the source levels of fin whales obtained from ocean bottom seismometer (OBS) data (Weirathmueller *et al.*, 2013). In order to convert fin whale detections to estimates of fin whale densities, we developed an automated technique to estimate the range of fin whale calls on a single OBS from multipaths and presented the results at the DCLDA workshop in St. Andrews (Weirathmueller and Wilcock, 2013).

3. *Net Sample and ADCP analysis.* In previous reporting periods, we analyzed over 50 net samples collected in 1995-6 during towed ADCP/CTD/Optics/Tucker trawl surveys near Endeavour Ridge to add to a 1991-4 historical database and used simultaneous acoustic backscatter and net tow data to obtain a calibration of the acoustic observations (Burd and Thomson, 2012). In this reporting period we examine ADCP and net tow data to determine how the vents may be affecting the depth-stratified secondary production of meso-zooplankton. We are also attempting to analyze long-term time series from upward looking ADCPs to determine if deep scattering layers at 1500-1900 m above the Endeavour hydrothermal vents are a seasonal phenomenon related to ontogenetic migrations of upper ocean fauna, or if they are a persistent, year-round assemblage.

RESULTS

Multipath Ranging. As long as the water depth is sufficient for differentiating between successive multipath arrivals (approximately 750m for a fin whale 20 Hz call), the timing and relative amplitude of multipath arrivals may be used to determine range (McDonald and Fox, 1999; Aubauer *et al*., 2000; Mellinger et al., 2009). We have investigated whether an automated implementation of this method might be viable for use with distance sampling techniques. Located calls from the Endeavour dataset (Soule and Wilcock, 2013) were used to ground truth range estimates. Timing and relative amplitude of multipath arrivals were modeled for a series of possible ranges using BELLHOP ray tracing and acoustic propagation software (Porter and Bucker, 1987). An automatic detection algorithm extracted segments of multipath time series from the recorded data. To amplify lower amplitude multipath arrivals in the recorded data, nearby calls are aligned and summed. The recorded segments were then compared with the modeled time series at each range step. The comparison was done by cross correlating the measured signal with the modeled signal, where the highest correlation value gives the best estimate of range.

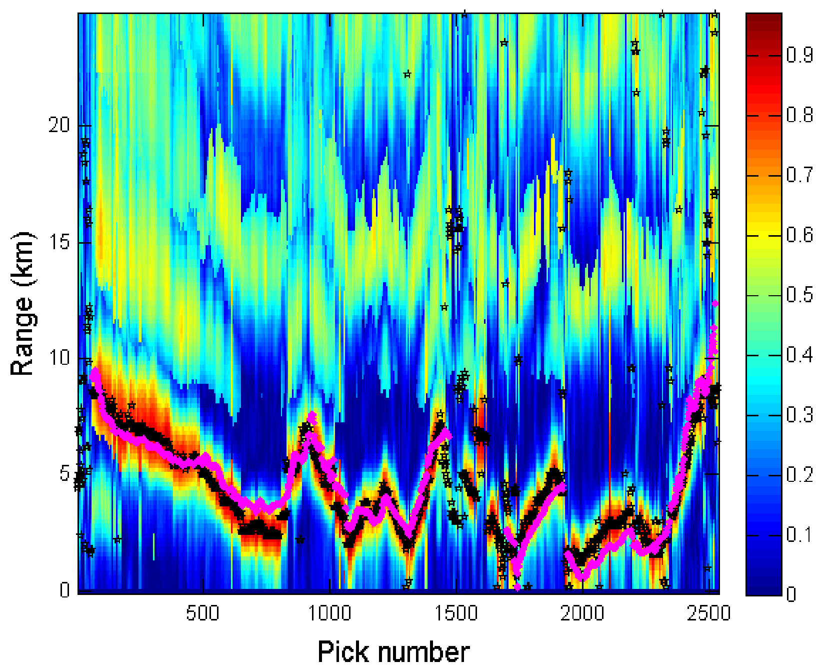

Fig 2. Range estimated using multipath spacing and amplitude for a series of fin whale calls in December 2003. Colors in the image indicate correlation on a scale from 0-1, with 1 being a perfect match. The maximum of each vertical slice corresponds to the closest match between measured multipath arrival and range model, and is annotated with a black star. Magenta dots show ranges from previously estimated call locations.

At the Endeavour site, the method is generally reliable for ranges up to ~10 km (Fig. 2). However, the complex bathymetry in the vicinity of the network complicates the implementation of the technique and limits the use of amplitudes to discriminate between alternate solutions in which the first observed arrival is either a direct path or first multiple because of the bathymetry can affect observed amplitudes through focusing effects. The multipath ranging technique is potentially very reliable and easy to implement in the regions of low-relief bathymetry. Initial testing using one of the Neptune Canada

stations at a mid-plate setting (ODP 1027 in Fig. 1) is very promising. The observed fin whale calls at this site often comprise overlapping call sequences from multiple whales but the amplitudes are more diagnostic of range and thus provide a useful additional constraint that can be incorporated into multipath range estimates.

Impacts of Hydrothermal Vents on secondary production. The epiplume fauna are a mixture of deep-sea organisms and mesopelagic ontogenetic migrators and their predators, once thought to be restricted to maximum depths of 800-900 m during their diapause phase in the northeast Pacific (Miller et al. 1984; Batchelder 1985; Terazaki and Miller 1986; and Miller and Clemons 1988). Near the vents, these diapausing migrators congregate above the plume in summer (Burd and Thomson 1995) where they resume feeding (Burd et al. 2002), thus increasing their reproductive output as evidenced by the enhanced concentration and diagnostic composition of lipids in ascending particles relative to background (Cowen et al. 2001; Wakeham et al. 2001). The vents are thought to impact regional food chains and organic carbon cycling throughout the water column. Wilcock et al. (2009) have discussed the possibility that whale-feeding patterns to 800 m depth may be influenced by the proximity of hydrothermal venting. However, the question remains: is the scale of the vent input sufficient to be translated into observable increased biomass or production in the upper ocean?

Because they are towed consistently upward from near-bottom and have detailed water volume estimates, the net data are considered the most reliable for total water column biomass and production estimates. On the other hand, the nets integrate biomass over a broad depth range, which has varied over the years, depending on specific requirements of the earlier studies. We have examined both types of data to determine how the vents may be affecting depth-stratified secondary production of meso-zooplankton for; (1) the 0-150 m depth surface primary production layer; (2) the 150-400 m depth upper ocean migratory range; (3) the 400-800 m depth mesopelagic layer (some migrators, many permanent); (4) the 800-1600 m depth, typically uniformly low biomass, layer; and (5) the 1600-2000 m depth epiplume scattering layer (where present).

Net tows clearly show a significant exponential-like decline in total water column biomass and production (depths 0-2000 m) with increasing distance from vent fields (Fig. 3). The ADCP data were less clear. When the ADCP data were split into upper (< 800 m) and lower (>800 m) depth segments, the difference was much clearer in the deep water column. We find that summer water column biomass from zooplankton below 800 m depth is at least as important as that from the upper 800 m, and should not be ignored in water column studies. Biomass enhancement of the water column from venting may occur at considerable distance from vent fields

Near-surface zooplankton biomass for different ranges from both net and ADCP measurements from this study are being compared with other studies in the northeast Pacific. Values in the present study range to considerably higher value than all other regions except the near-coastal areas, with highest values proximal to the vents. Background values were similar to those found elsewhere in the northeast Pacific. Production values were similar with other studies, although this aspect has been studied in much less detail in the northeast Pacific.

Annual cycles in backscatter intensity. Extensive work has been conducted on the biomass, production, and spatial distribution of summer epiplume scattering layers over the depth range 1500-1900 m near the hydrothermally active vent fields of the Endeavour Ridge Marine Protected Area in the northeast Pacific. These layers are dominated in summer by meso-pelagic ontogenetic migrators which utilize extraordinary organic carbon from plume particulates. Until now, there has been

insufficient data to determine if these deep scattering layers are a seasonal phenomenon related to ontogenetic migrations of upper ocean fauna, or if they are a persistent, year-round assemblage. If a seasonal phenomenon, it is important to determine whether these layers migrate vertically, and when are they most intense.

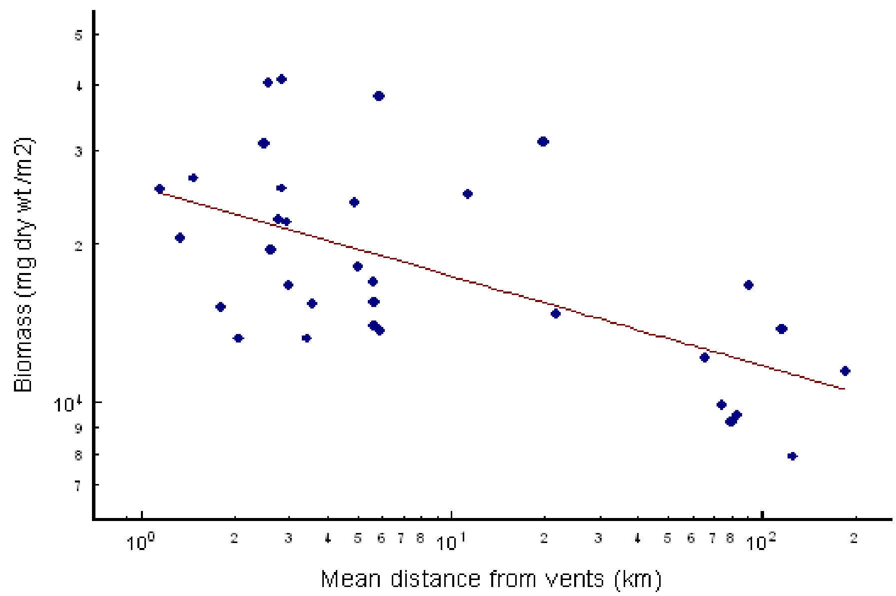

Fig 3. Total water column biomass over the depth range 0-2000 m from net samples relative to distance from the main Endeavour vent fields. The exponential regression was significant to $p < 0.01$.

Sensor data from the Ocean Networks Canada (ONC) cabled observatory (Fig. 4) makes it possible to conduct new, in-depth studies of biophysical processes at Endeavour Ridge. Data from two moorings, Regional Circulation Mooring Northeast (RCM-NE) and Northwest (RCM-NW), are available for analysis from October 28, 2010 to May 5, 2012. The moorings are situated 600 m from one another across the axial valley (Fig. 4), each with an upward-looking 75 kHz acoustic Doppler current profiler (ADCP) that records acoustic backscatter intensity through the lower 1000 m of the water column. At present, we are dealing with instrument calibration issues with the existing data, which, when resolved, will allow us to characterize deep scattering layers with depth and time near Endeavour Ridge. Fig. 5 shows a set of waterfall plots showing the depth distributions of acoustic anomalies for the northeast mooring following removal of the one-year record mean values at each 8-m depth bin.

Because of cable and hardware interface problems, the Ocean Networks Canada current meter moorings are no longer providing data. The moorings are in-place but not connected to the observatory system so it is not possible to examine longer-term backscatter data for this study. In an attempt to compensate for the cabled data series, we are assembling all historical bottom mounted ADCP data from the region to determine if we can define the seasonal cycle without relying on the cabled moorings.

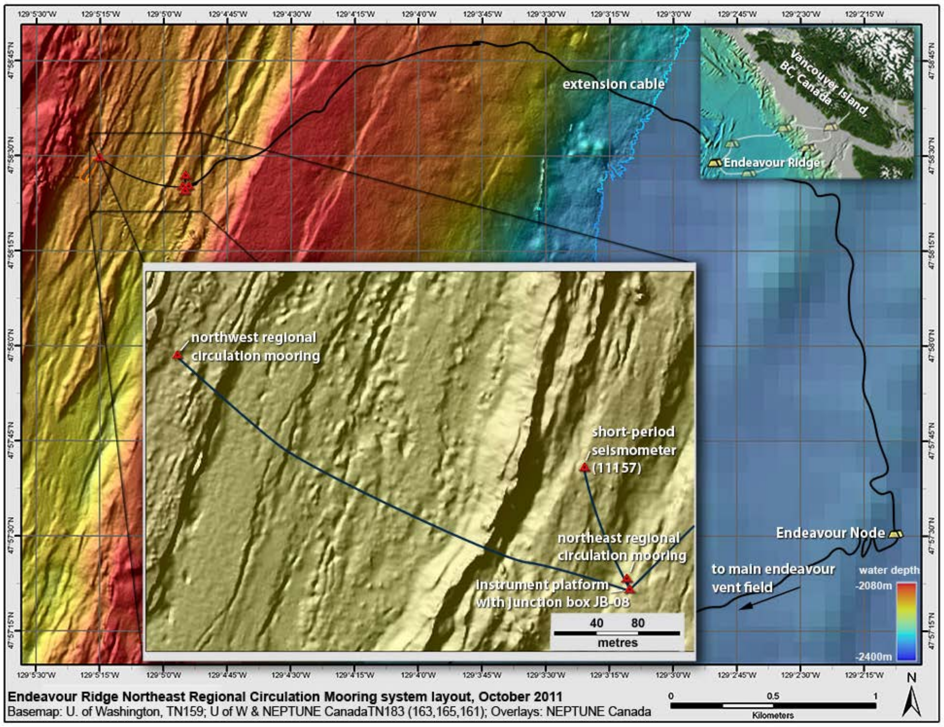

Fig. 4. Location of the two Ocean Networks Canada moorings to the NE and NW of the main Endeavour Ridge axial valley. The moorings are still in place but are no longer connected to the cabled observatory.

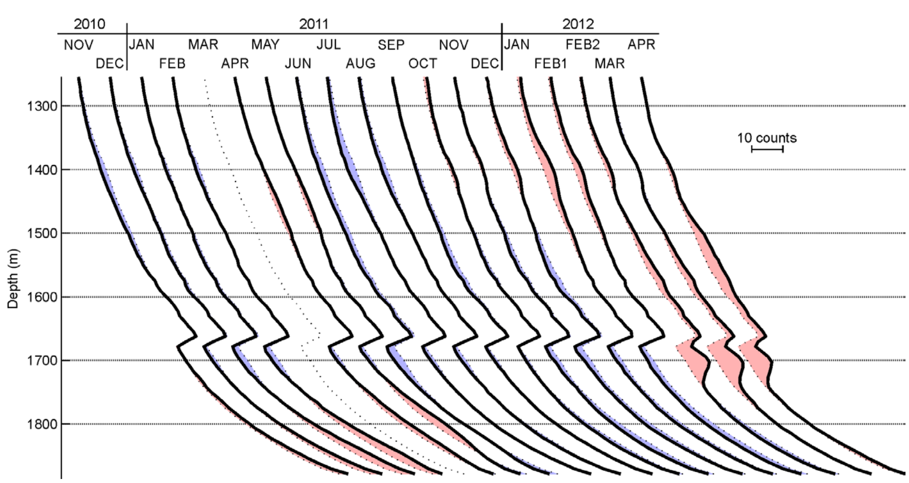

Fig. 5. Monthly mean "water fall plots" for 2010 to 2012 showing positive (red) and negative (blue) acoustic backscatter anomalies (in counts) over the depth range of the instrument at 8-m vertical resolution. The annual means have been subtracted from the original records at all depth bins to obtain the anomalies. The depth-related attenuation of the signal is related to distance from the upward-looking 75 kHz ADCP moored at 250 m above bottom.

IMPACT/APPLICATIONS

We have developed automatic fin whale detection, location and ranging algorithms that can be applied to other seafloor seismic networks. The location and ranging algorithms could be adapted to other vocalizing species (or anthropogenic sounds) recorded by a network of seafloor receivers provided the calls are sufficiently short and spaced far enough apart so that the direct and multiple arrivals do not overlap. The double difference method is commonly used in earthquake studies but has not previously been applied to marine mammals. The close relationship between biomass and acoustic backscatter provides a method to extrapolate limited net tow data to images of the 3-D distribution of biomass and has been used to infer that secondary production is enhanced by the hydrothermal vent fields. If a correlation if found between the distribution of whales, enhanced zooplankton concentrations and hydrothermal vents it will have implications for our understanding of the global influences of hydrothermal vents on the trophic ecology of the ocean (Gisiner *et al.*, 2009).

RELATED PROJECTS

The Endeavour node on the NEPTUNE Canada regional cabled observatory will when fully instrumented include a water column experiment that will monitor deep macrozooplankton concentrations (Rick Thomson is the lead-PI) and a seafloor seismic network (William Wilcock is a co-PI). The amphibious portion of Cascadia Initiative is an ambitious NSF project that is deploying 70 OBSs for 4 years at ~160 sites over the Juan de Fuca plate and Cascadia margin from approximately 40°N to 50°N, thus providing the opportunity to investigate the broader spatial and temporal distribution of fin and blue whales.

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